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ABSTRACT

Three alternative solutions available for analysis of variance (ANOVA) using two-way and three-way completely randomized factorial designs with disproportional cell sizes across all two-way and three-way summary tables with no empty cells are discussed. These solutions are categorized as unique, sequential, and experimental. The procedures used, the Statistical Package for the Social Sciences-X (SPSSX) (release 3.1) ANOVA and multivariate analysis of variance (MANOVA) procedures and the Statistical Analysis System (SAS) (release 5.18) general linear models (GLM) procedure, report the same results for only the unique solution for each effect. Similarities as well as differences were found among the sequential and experimental solutions. Comparisons across the three software procedures were demonstrated by illustrating the adjustment procedures to effects through the use of multiple regression and orthogonal coding. It is evident that caution needs to be exercised in the interpretation of the results from the three software procedures and in relating the results to textbooks in the behavioral sciences. Eight data tables and three figures are provided. (TJH)

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Alternative Solutions for ANOVA using 2-way and 3-way Completely Randomized Factorial Designs with Disproportional Cell Sizes

by

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Three alternative solutions available for ANOVA using 2-way and 3-way completely randomized factorial designs with disproportional cell sizes across all 2-way and 3-way summary tables with no empty cells are discussed. SPSSX ANOVA (i. e., release 3.1), SPSSX MANOVA (i. e., release 3.1, and SAS PROC GLM (i. e., release 5.18), report the same results for only the unique solution for each effect. Similarities as well as differences were found among the sequential and experimental solutions. Comparisons across the three software procedures were demonstrated by illustrating the adjustment procedures to effects through the use of multiple regression and orthogonal coding. It is evident that caution needs to be exercised in the interpretation of the results from the three software procedures and in relating the results to textbooks in the behavioral sciences.

Alternative Solutions for ANOVA using 2-way and 3-way Completely Randomized Factorial Designs with Disproportional Cell Sizes

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In general, there are three alternative solutions available for ANOVA using 2-way and 3-way completely randomized factorial designs with disproportional cell sizes across all 2-way and 3-way summary tables with no empty cells. Although different names are used to refer to these solutions by different sources, this presentation labels the solutions (1) unique, (2) sequential, and (3) experimental. SPSSX ANOVA (i. e., release 3.1), SPSSX MANOVA (i. e., release 3.1), and SAS PROC GLM (i. e., release 5.18), three software procedures common in the social sciences, report the same results for only one of these alternative solutions--the unique solution for each effect. Glass and Hopkins (1984) state that for most purposes, researchers tend to favor the most conservative alternative--the one in which the effect being tested is required to add unique information with respect to all other parameters in the model. That is, a solution in which each effect, regardless whether it is a main effect or an interaction, is adjusted for relationship to all other effects in the model. Therefore, it appears that the alternative solution most preferred among researchers may be the one for which there is agreement among the three software procedures.

The definitions for the other two solutions, sequential and experimental, differ across the three software procedures. The descriptions of the solutions in the manuals for the three software procedures use different vocabulary in describing the solutions and adjustments to effects. Selected recent textbooks in the behavioral sciences, one by Hays (1988) and another by Kirk (1982), also define alternative solutions and adjustment procedures and they do not use the same vocabulary in defining them. One purpose of this presentation is to relate the solutions of the software procedures to the solutions described in these two textbooks and to point out similarities and dissimilarities between the textbooks and the three software procedures. A second purpose is to depict the definitions of the adjustments to effects for the three alternative solutions used in the software procedures and to clarify the similarities and dissimilarities among the procedures.

The adjustment procedures for these ANOVA designs can be viewed as a multiple regression problem. Consider coding the various levels

of the ANOVA classification variables by using quantitative contrast coefficients. Although any number of coding schemes might be used to obtain the tests of significance, suppose the selected coding scheme is made equivalent to a set of planned orthogonal ANOVA contrasts. These contrasts can be used to define predictor variables and squared multiple correlation coefficients between them and the dependent variable can be computed. These squared multiple correlation coefficients, when multiplied by the total sum of squares, will generate the sum of squares for a source of variation in a particular model. Differences between squared multiple correlation coefficients will generate squared part correlation coefficients that are reflective of adjustments to sources of variation.

For example, suppose we wish to compute the sum of squares for main effect A adjusted by main effect B and the AB interaction (i. e., source A|B, AB) in a two-way design. The following steps can be performed:

Step 1: Generate a squared multiple correlation coefficient ($R^2_{Y \cdot A,B,AB}$) between the dependent variable (Y) and predictor variables as defined by orthogonal contrast coefficients for the A main effect, the B main effect, and the AB interaction.

Step 2: Generate a squared multiple correlation coefficient ($R^2_{Y \cdot B,AB}$) between the dependent variable (Y) and predictor variables as defined by orthogonal contrasts for only the B main effect and the AB interaction removing the orthogonal contrasts for the A main effect from the model.

Step 3: Find the difference between these two squared multiple correlation coefficients. It is equal to the square of the part correlation [$r^2_{Y(A \cdot B,AB)}$] between the dependent variable (Y) and the A main effect adjusted by the B main effect and the AB interaction.

Step 4: Multiply the squared part correlation coefficient by the total sum of squares (SS_{Total}). This product is the sum of squares (SS) for the source A|B, AB.

Steps 1-3: $$r^2_{Y(A \cdot B,AB)} = R^2_{Y \cdot A,B,AB} - R^2_{Y \cdot B,AB}$$

Step 4: $$SS_{A|B,AB} = SS_{Total} \times r^2_{Y(A \cdot B,AB)}$$

In a similar manner, the sum of squares for each source in the following models can be conceptualized as the product of a squared part correlation coefficient and the total sum of squares.

The adjustment to effects are presented by listing each effect in a 2-way design and a 3-way design and stating the adjustment to each. It should be evident that caution needs to be exercised in the interpretation of the results from the three software procedures and in relating the results to textbooks in the behavioral sciences.

Solution I. UNIQUE SOLUTION FOR EACH EFFECT. This solution adjusts each effect for relationship to all other effects in the model.

A. Kirk's Method I

2-way:

SSR(A|B,AB)
SSR(B|A,AB)
SSR(AB|A,B)
SSE

3-way: none reported

B. Hays' Method R (The Regression Approach)

2-way:

Factor A, beyond B, AB
Factor B, beyond A, AB
AB, beyond Factors A, B
E

3-way: none reported

C. SPSSX ANOVA Unique (or Regression)
D. SPSSX MANOVA Unique (the default used by SPSSX MANOVA)
E. SAS PROC GLM Type III

All of these software procedures report the same results for a 2-way design. They also report the same results for a 3-way design.

2-way:

A|B, AB
B|A, AB
AB|A, B
E

3-way:

A|B, C, AB, AC, BC, ABC
B|A, C, AB, AC, BC, ABC
C|A, B, AB, AC, BC, ABC
AB|A, B, C, AC, BC, ABC
AC|A, B, C, AB, BC, ABC
BC|A, B, C, AB, AC, ABC
ABC|A, B, C, AB, AC, BC
E

Solution II. SEQUENTIAL SOLUTION FOR ORDERED EFFECTS. This solution depends on an a priori ordering of effects in the model and each effect is adjusted only for those preceding it in the model.

A. Kirk's Method IIIa and IIIb

2-way (in order of A, B, AB)

SSR(A)
SSR(B|A)
SSR(AB|A,B)
SSE

3-way: none reported

B. Hays' Method H (The Hierarchical Approach)

2-way (in order of A, B, AB)

Factor A
Factor B, beyond A
AB, beyond Factors A, B

3-way: none reported

C. SPSSX ANOVA Hierarchical: SPSSX ANOVA Hierarchical adjusts the main effects in a sequential manner for both a 2-way design and a 3-way design. The main effects need to be specified in different orders to change their adjustments.

2-way (specified in order of A, B, AB): The main effects are listed in the order of A, B. This results in the A main effect not being adjusted while the B main effect is adjusted for A. If the order were changed so that the B main effect is listed first and the A main effect listed second, the adjustments will change so that the B main effect is not adjusted for the other effects but the A main effect will be adjusted for the B main effect . The first order interaction is adjusted for the two main effects.

A
B|A
AB|A, B
E

Solution II. SEQUENTIAL SOLUTION FOR ORDERED EFFECTS (continued)

C. SPSSX ANOVA Hierarchical (continued)

3-way (specified in order of A, B, C, AB, AC, BC, ABC): The main effects are listed in the order of A, B, C. This results in the A main effect not being adjusted, the B main effect being adjusted for A, and the C main effect being adjusted for A and B. If the order were changed by listing either main effect B or main effect C first, the adjustment to each main effect will change in a manner similar to the adjustments to the main effects of a 2-way design. All first order interactions are adjusted for all main effects AND all other first order interactions regardless of their order (i. e., not sequentially). The second order interaction is adjusted for all main effects AND all first order interactions.

A
B|A
C|A, B
AB|A, B, C, AC, BC
AC|A, B, C, AB, BC
BC|A, B, C, AB, AC
ABC|A, B, C, AB, AC, BC
E

D. SPSSX MANOVA Sequential
E. SAS PROC GLM Type I

SPSSX MANOVA Sequential and SAS PROC GLM Type I report the same results for a 2-way design and the same results for a 3-way design. They adjust both the main effects AND the first order interactions sequentially. Therefore, it is important to note the order of the main effects AND the first order interactions. This is the only solution in which the sum of the SS for sources is equal to the Total SS. The sequential adjustment to the first order interactions is different from the adjustment that occurs with SPSSX ANOVA Hierarchical since only the main effects are adjusted sequentially by SPSSX ANOVA.

2-way (in order of A, B, AB): Since there is only one interaction effect in a 2-way design, SPSSX MANOVA Sequential, SAS PROC GLM Type I, and SPSSX ANOVA Hierarchical report the same results.

A
B|A
AB|A, B
E

Solution II. SEQUENTIAL SOLUTION FOR ORDERED EFFECTS (continued)

D. SPSSX MANOVA Sequential (continued)
E. SAS PROC GLM (Type I) (continued)

3-way (in order of A, B, C, AB, AC, BC, ABC). Since both the main effects and first order interactions are adjusted sequentially by SPSSX MANOVA Sequential and SAS PROC GLM Type I, only the main effects, the last ordered first order interaction, and the second order interaction report the same results as SPSSX ANOVA Hierarchical.

A
B|A
C|A, B
AB|A, B, C
AC|A, B, C, AB
BC|A, B, C, AB, AC
ABC|A, B, C, AB, AC, BC
E

Solution III. EXPERIMENTAL SOLUTION. This solution is based on an experimental design of main effect and interaction levels.

A. Kirk's Method II

2-way:

SSR(A|B)
SSR(B|A)
SSR(AB|A, B)
E

3-way: none reported

B. Hays' does not define a solution similar to this one but does briefly refer to the classic experimental solution defined by SPSSX ANOVA Experimental.

C. SPSSX ANOVA Experimental (classic experimental): This solution is the default of SPSSX ANOVA. It is similar to the SPSSX ANOVA Hierarchical solution in that it adjusts the first order interactions for the main effects. It is different from the SPSSX ANOVA Hierarchical in that it adjusts each of the main effects for the other main effects and does not order them sequentially.

2-way:

A|B
B|A
AB|A, B
E

3-way:

A|B, C
B|A, C
C|A, B
AB|A, B, C, AC, BC
AC|A, B, C, AB, BC
BC|A, B, C, AB, AC
ABC|A, B, C, AB, AC, BC
E

Solution III. EXPERIMENTAL SOLUTION (continued)

D. SPSSX MANOVA does not define a solution similar to this one.

E. SAS PROC GLM Type II: SAS PROC GLM Type II is the same as SPSSX ANOVA Experimental for a 2-way design but differs from SPSSX ANOVA Experimental for a 3-way design in that it adjusts each main effect for not only the other main effects but also the interaction of the other two main effects.

2-way: In a 2-way design, the two solutions (i.e., SPSSX ANOVA Experimental and SAS PROC GLM Type II) report the same results.

A|B
B|A
AB|A, B
E

3-way: In a 3-way design, each of the main effects are adjusted for the other two main effects and their interaction. The adjustment to the main effect including the interaction causes SAS PROC GLM Type II main effects to differ from SPSSX ANOVA Experimental main effects. The first and second order interactions for SAS PROC GLM Type II report the same SS as SPSSX Experimental indicating that the same adjustments are used.

A|B, C, BC
B|A, C, AC
C|A, B, AB
AB|A, B, C, AC, BC
AC|A, B, C, AB, BC
BC|A, B, C, AB, AC
ABC|A, B, C, AB, AC, BC
E

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Table 1. Example data set from Kirk (1982) for a disproportional 2-way design.

	Cells								
	A1 B1	A1 B2	A1 B3	A2 B1	A2 B2	A2 B3	A3 B1	A3 B2	A3 B3
Cell Size	4	5	5	5	5	5	5	5	5
Data	24	44	38	30	35	26	21	41	42
	33	36	29	21	40	27	18	39	52
	37	25	28	39	27	36	10	50	53
	29	27	47	26	31	46	31	36	49
		43	48	34	22	45	20	34	64

Table 2. ANOVA of 2-way example data set with a UNIQUE solution using SPSS^X ANOVA Unique, SPSS^X MANOVA Unique, and SAS PROC GLM TYPE III

Source	SS
A|B, AB	188.09
B|A, AB	1641.29
AB|A, B	1117.42
Error	2148.75
Total N = 44	

Figure 1. Orthogonal coding for the data set from Kirk for a disproportional 2-way design.

	A		B		AB				
	A1	A2	B1	B2	A1B1	A1B2	A2B2	A2B2	Y[1]
a_1b_1	1	.5	1	.5	1	.5	.5	.25	24
a_1b_2	1	.5	-1	.5	-1	.5	-.5	.25	44
a_1b_3	1	.5	0	-1	0	-1	0	-.5	38
a_2b_1	-1	.5	1	.5	-1	-.5	.5	.25	30
a_2b_2	-1	.5	-1	.5	1	-.5	-.5	.25	35
a_2b_3	-1	.5	0	-1	0	1	0	-.5	26
a_3b_1	0	-1	1	.5	0	0	-1	-.5	21
a_3b_2	0	-1	-1	.5	0	0	1	-.5	41
a_3b_3	0	-1	0	-1	0	0	0	1	42

[1]Coding for the first observation of each cell is presented as representative of the coding for all observations within that cell.

Table 5. Modified example data set from Lindquist (1953) for a 3-way disproportional design[1]

	Cells																							
	A1 B1 C1	A1 B1 C2	A1 B1 C3	A1 B2 C1	A1 B2 C2	A1 B2 C3	A1 B3 C1	A1 B3 C2	A1 B3 C3	A1 B4 C1	A1 B4 C2	A1 B4 C3	A2 B1 C1	A2 B1 C2	A2 B1 C3	A2 B2 C1	A2 B2 C2	A2 B2 C3	A2 B3 C1	A2 B3 C2	A2 B3 C3	A2 B4 C1	A2 B4 C2	A2 B4 C3
Cell Size	3	2	4	5	4	6	7	6	8	4	3	5	4	3	2	6	5	4	7	6	5	5	4	3
Data	7	13	10	7	10	9	16	9	20	9	19	17	13	10	14	17	16	16	25	19	22	30	15	17
	7	16	10	5	13	13	12	13	17	17	10	11	12	18	19	22	7	15	18	21	17	21	6	23
	14		15	15	13	7	16	7	13	9	21	15	18	20		14	13	11	25	15	17	9	16	17
			18	12	14	13	10	13	16	22		12	18			17	16	13	15	15	11	13	18	
				11		12	9	7	9			14				10	9		21	12	24	18		
						8	11	9	14							12			18	18				
							12		14										30					
									12															

[1]Original data set from Lindquist (1953) was for a proportional design. Cases were eliminated to create a disproportional design across all 2-way and 3-way summary tables.

Figure 2. Orthogonal coding for the first 11 effects for the modified data set from Lindquist (1953) for a 3-way disproportional design.

	A	B			C		AB			AC		
	A	B1	B2	B3	C1	C2	AB1	AB2	AB3	AC1	AC2	Y[1]
$a_1b_1c_1$	1	1	0	.5	1	.5	1	0	.5	1	.5	7
$a_1b_1c_2$	1	1	0	.5	-1	.5	1	0	.5	-1	.5	13
$a_1b_1c_3$	1	1	0	.5	0	-1	1	0	.5	0	-1	10
$a_1b_2c_1$	1	-1	0	.5	1	.5	-1	0	.5	1	.5	7
$a_1b_2c_2$	1	-1	0	.5	-1	.5	-1	0	.5	-1	.5	10
$a_1b_2c_3$	1	-1	0	.5	0	-1	-1	0	.5	0	-1	9
$a_1b_3c_1$	1	0	1	-.5	1	.5	0	1	-.5	1	.5	16
$a_1b_3c_2$	1	0	1	-.5	-1	.5	0	1	-.5	-1	.5	9
$a_1b_3c_3$	1	0	1	-.5	0	-1	0	1	-.5	0	-1	20
$a_1b_4c_1$	1	0	-1	-.5	1	.5	0	-1	-.5	1	.5	9
$a_1b_4c_2$	1	0	-1	-.5	-1	.5	0	-1	-.5	-1	.5	19
$a_1b_4c_3$	1	0	-1	-.5	0	-1	0	-1	-.5	0	-1	17
$a_2b_1c_1$	-1	1	0	.5	1	.5	-1	0	-.5	-1	-.5	13
$a_2b_1c_2$	-1	1	0	.5	-1	.5	-1	0	-.5	1	-.5	10
$a_2b_1c_3$	-1	1	0	.5	0	-1	-1	0	-.5	0	1	14
$a_2b_2c_1$	-1	-1	0	.5	1	.5	1	0	-.5	-1	-.5	17
$a_2b_2c_2$	-1	-1	0	.5	-1	.5	1	0	-.5	1	-.5	16
$a_2b_2c_3$	-1	-1	0	.5	0	-1	1	0	-.5	0	1	16
$a_2b_3c_1$	-1	0	1	-.5	1	.5	0	-1	.5	-1	-.5	25
$a_2b_3c_2$	-1	0	1	-.5	-1	.5	0	-1	.5	1	-.5	19
$a_2b_3c_3$	-1	0	1	-.5	0	-1	0	-1	.5	0	1	22
$a_2b_4c_1$	-1	0	-1	-.5	1	.5	0	1	.5	-1	-.5	30
$a_2b_4c_2$	-1	0	-1	-.5	-1	.5	0	1	.5	1	-.5	15
$a_2b_4c_3$	-1	0	-1	-.5	0	-1	0	1	.5	0	1	17

[1]Coding for the first observation of each cell is presented as representative of the coding for all observations within that cell.

Figure 3. Continuation of the orthogonal coding for the modified data set from Lindquist (1953) for a 3-way disproportional design.

	BC						ABC						
	B_1C_1	B_1C_2	B_2C_1	B_2C_2	B_3C_1	B_3C_2	AB_1C_1	AB_1C_2	AB_2C_1	AB_2C_2	AB_3C_1	AB_3C_2	Y^1
$a_1b_1c_1$	1	.5	0	0	.5	.25	1	.5	0	0	.5	.25	7
$a_1b_1c_2$	-1	.5	0	0	-.5	.25	-1	.5	0	0	-.5	.25	13
$a_1b_1c_3$	0	-1	0	0	0	-.5	0	-1	0	0	0	-.5	10
$a_1b_2c_1$	-1	-.5	0	0	.5	.25	-1	-.5	0	0	.5	.25	7
$a_1b_2c_2$	1	-.5	0	0	-.5	.25	1	-.5	0	0	-.5	.25	10
$a_1b_2c_3$	0	1	0	0	0	-.5	0	1	0	0	0	-.5	9
$a_1b_3c_1$	0	0	1	.5	-.5	-.25	0	0	1	.5	-.5	-.25	16
$a_1b_3c_2$	0	0	-1	.5	.5	-.25	0	0	-1	.5	.5	-.25	9
$a_1b_3c_3$	0	0	0	-1	0	.5	0	0	0	-1	0	.5	20
$a_1b_4c_1$	0	0	-1	-.5	-.5	-.25	0	0	-1	-.5	-.5	-.25	9
$a_1b_4c_2$	0	0	1	-.5	.5	-.25	0	0	1	-.5	.5	-.25	19
$a_1b_4c_3$	0	0	0	1	0	.5	0	0	0	1	0	.5	17
$a_2b_1c_1$	1	.5	0	0	.5	.25	-1	-.5	0	0	-.5	-.25	13
$a_2b_1c_2$	-1	.5	0	0	-.5	.25	1	-.5	0	0	.5	-.25	10
$a_2b_1c_3$	0	-1	0	0	0	-.5	0	1	0	0	0	.5	14
$a_2b_2c_1$	-1	-.5	0	0	.5	.25	1	.5	0	0	-.5	-.25	17
$a_2b_2c_2$	1	-.5	0	0	-.5	.25	-1	.5	0	0	.5	-.25	16
$a_2b_2c_3$	0	1	0	0	0	-.5	0	-1	0	0	0	.5	16
$a_2b_3c_1$	0	0	1	.5	-.5	-.25	0	0	-1	-.5	.5	.25	25
$a_2b_3c_2$	0	0	-1	.5	.5	-.25	0	0	1	-.5	-.5	.25	19
$a_2b_3c_3$	0	0	0	-1	0	.5	0	0	0	1	0	-.5	22
$a_2b_4c_1$	0	0	-1	-.5	-.5	-.25	0	0	1	.5	.5	.25	30
$a_2b_4c_2$	0	0	1	-.5	.5	-.25	0	0	-1	.5	-.5	.25	15
$a_2b_4c_3$	0	0	0	1	0	.5	0	0	0	-1	0	-.5	17

[1]Coding for the first observation of each cell is presented as representative of the coding for all observations within that cell.

Table 3. ANOVA of 2-way example data set with a SEQUENTIAL solution using SPSS^X ANOVA Hierarchical, SPSS^X MANOVA Sequential, and SAS PROC GLM Type I.

Source	SS
(Analyzed in the order of A, B, AB)	
A	187.51
B|A	1716.21
AB|A, B	1117.42
Error	2148.75
[1]Total	5169.89
Total N = 44	

[1]Total SS equal to the sum of the SS for sources.

Table 4. ANOVA of 2-way example data set with an EXPERIMENTAL solution using SPSS^X ANOVA Experimental and SAS PROC GLM Type II.

Source	SS
A|B	190.38
B|A	1716.21
AB|A, B	1117.42
Error	2148.75
Total N = 44	

Table 6. ANOVA of 3-way example data set with a UNIQUE solution using SPSS^X ANOVA Unique, SPSS^X MANOVA Unique, and SAS PROC GLM TYPE III

Source	SS
A|B, C, AB, AC, BC, ABC	351.85
B|A, C, AB, AC, BC, ABC	221.63
C|A, B, AB, AC, BC, ABC	12.62
AB|A, B, C, AC, BC, ABC	103.60
AC|A, B, C, AB, BC, ABC	96.41
BC|A, B, C, AB, AC, ABC	109.20
ABC|A, B, C, AB, AC, BC	79.22
Error	1526.35
Total N = 111	

Table 7. ANOVA of 3-way example data set with a SEQUENTIAL solution using SPSS^X ANOVA Hierarchical, SPSS^X MANOVA Sequential, and SAS PROC GLM Type I

Source	SS
(Analyzed in the order of A, B, C, AB, AC, BC, ABC)	
A	486.61
B|A	232.41
C|A, B	50.66
[1]AB|A, B, C	93.48
[2]AB|A, B, C, AC, BC	102.24
[1]AC|A, B, C, AB	84.07
[2]AC|A, B, C, AB, BC	94.63
BC|A, B, C, AB, AC	114.57
ABC|A, B, C, AB, AC, BC	79.22
Error	1526.35
Total SS	2667.37
Total N = 111	

[1]Reported for SPSS^X MANOVA Sequential and SAS PROC GLM Type I only. Total SS is equal to the sum of the SS for sources.

[2]Reported for SPSS^X ANOVA Hierarchical only. Total SS is <u>not</u> equal to the sum of the SS for sources because the first order interactions are <u>not</u> analyzed sequentially.

Table 8. ANOVA of 3-way example data set with an EXPERIMENTAL solution using SPSS^X ANOVA Experimental and SAS PROC GLM Type II

Source	SS
[1]A|B, C	514.99
[2]A|B, C, BC	512.94
[1]B|A, C	233.59
[2]B|A, C, AC	233.21
[1]C|A, B	50.66
[2]C|A, B, AB	48.23
AB|A, B, C, AC, BC	102.24
AC|A, B, C, AB, BC	94.63
BC|A, B, C, AB, AC	114.57
ABC|A, B, C, AB, AC, BC	79.22
Error	1526.35
Total N = 111	

[1]Reported for SPSS^X ANOVA Experimental only.

[2]Reported for SAS PROC GLM Type II only.